Stereo-on-a-Chip [STOC]
Stereo Head
User Manual 1.2

August, 2006

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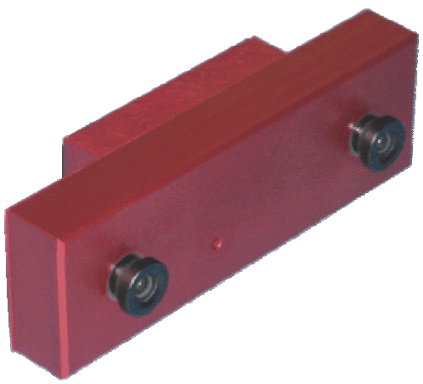

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1 Introduction

The STOC is a new type of device. It functions as a complete *vision processor*, combining stereo cameras and an embedded processor to produce 3D stereo information. The processor was developed at SRI International's Artificial Intelligence Lab, for use in real-time vision and robotics projects. Because the embedded processor has been designed for just this task, it is more capable than the fastest PC, achieving over 40 Gops (40 billion operations per second). And it does this at a fraction of the power – just 0.8 watts for the processor, and 2.4 watts for the whole device. The result is an output stream of 3D information, at a resolution of 640x480, at 30 frames per second.

The stereo cameras are 640x480 (VGA), progressive scan CMOS imagers mounted in a rigid body. They have a *global shutter* – all pixels are exposed at exactly the same time. This makes the STOC suitable for environments with fast movement, such as on an outdoor vehicle. The imagers have excellent dynamic range, sensitivity, anti-blooming, and noise characteristics. They are fully controllable: the user can set exposure, gain, decimation, etc.

The STOC uses standard miniature lenses, or standard CS-mount lenses, for user-changeable optics. Wide-angle to telephoto options are available, depending on the application. The device comes fully calibrated, ready to produce 3D information out of the box. A simple, in-field calibration procedure is available if the lenses are changed.

The STOC has an IEEE 1394 (FireWire) interface for output and power. It connects to any 6-pin FW port, and delivers real-time 3D information using the DCAM 1.30 standard.

SRI's Small Vision System (SVS) software has an interface to the STOC, and is included with each stereo head. The SVS software includes software drivers for the STOC for MS Windows 98SE/ME/2000/XP, and for Linux 2.4.and 2.6 kernels.

1.1 Characteristics of stereo system

- *On-device stereo processing*
  Xilinx Spartan 3 – 1000 processor, 88 MHz
  512 KB SRAM
- *Stereo Processing*
  640x480, 64 disparities @ 30 Hz
  Subpixel interpolation of disparity to 1/16 pixel
  15x15 correlation window
  9x9 Laplacian of Gaussian preprocessing kernel
  Post-processing uniqueness check
  9 cm baseline
- *Fully calibrated for lens distortion at the factory*
  Recalibration in the field for change of lenses
- *Firmware upgrades via IEEE1394 connection*
- *Power: 0.84 W for stereo processing, 2.4 W total*

1.2 Characteristics of imagers

- ***Micron MT9V022 CMOS imagers***
  - ***Global shutter***
  - ***Simultaneous exposure and readout – true 30 fps***
  - ***640x480 maximum image size***
  - ***1/3" format***
  - ***High sensitivity, low noise***
  - ***Low pixel cross-talk***
- ***Fully synchronized stereo – left and right pixels are interleaved in the video stream***
- ***Monochrome or Bayer Color***
- ***High frame rates – 30 Hz for 640x480***
- ***Extensive control of video parameters***
  - ***Automatic or manual control of exposure and gain***

Automatic control of black level
Manual control of color balance

- ***50 Hz mode – reduces indoor light interference in countries with 50 Hz electrical line frequency***

1.3 General

- ***Stereo calibration information stored on the device***
- ***IEEE 1394 interface to standard PC hardware***
  Carries power and commands to device, data to PC
  DCAM 1.30 compatible
- ***Miniature 12mm diameter or CS-mount lenses, interchangeable |Standard focal lengths 2.1,3.6, and 6.5 mm]***
- ***Anodized aluminum alloy chassis, high rigidity***

1.4 Stereo analysis

The STOC board runs an optimized version of the SRI Small Vision System (SVS) stereo algorithms. This version produces the same results as SVS running on a standard PC, but is implemented inside the stereo device on a small reconfigurable processor, called a Field Programmable Gate Array (FPGA). The use of the FPGA frees up the host PC from the expensive stereo calculations, and makes it available for all of the user's application code.

Figure 1-1 shows typical results from SVS and the STOC device. On the left is one of the input images from the stereo cameras. The stereo images are processed to produce a range image, also called a *disparity image*, which encodes the distance to each pixel in the image, based on triangulating matched regions in the left and right images. In the disparity image, brighter areas indicate pixels that are closer. From the disparity image, the 3D structure of objects can be re-created, as in the two images on the right.

The STOC device comes pre-calibrated, so that lens distortions are automatically removed from the images (the results are called *rectified*images). There is no need to perform any calibration steps – the STOC is ready to start producing range results out of the box. However, you may want to change the lenses at some point, and the device can easily be recalibrated in the field, just like other Videre stereo devices.

More information about the stereo processing algorithm can be found in the technical pages for SVS, at www.ai.sri.com/~konolige/svs.

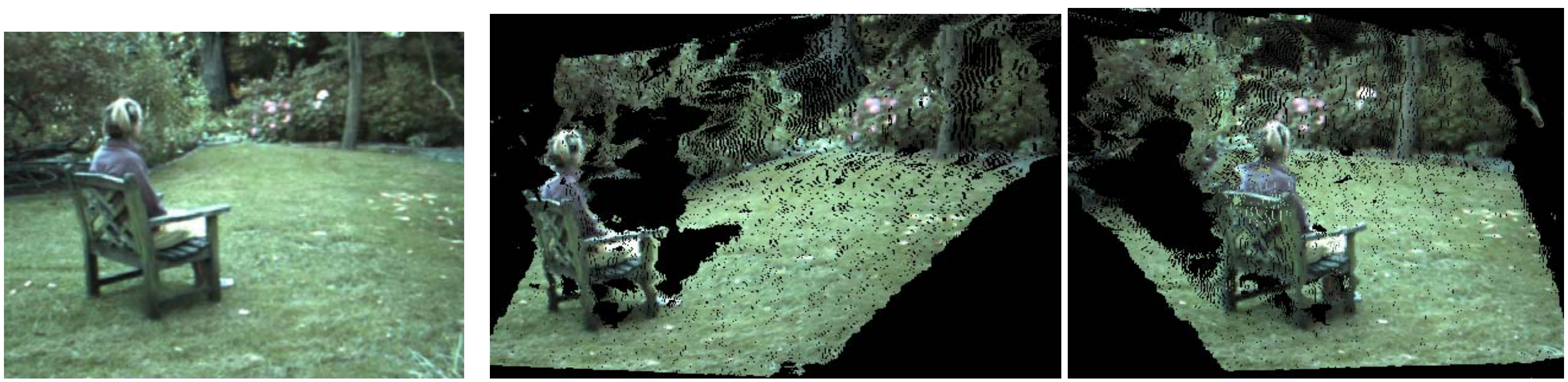


Figure 1-1 Stages in STOC processing. Left is one of the input images from the stereo imagers. The other two images show different 3D views reconstructed from the disparity data.

1.5 Global Shutter

The STOC has a global shutter. Almost all other CMOS imagers have a *rolling* shutter. With rolling shutter, each row of pixels is exposed just before it is read out. So each row is exposed at a different time from other rows. This leads to *motion blur* – a skewing of moving objects from top to bottom.

Global shutter, on the other hand, exposes every pixel at the same time. The charge on exposed pixels is then transferred to a set of storage bins, and read out to give an image. Because the pixels are exposed at the same time, there is no motion blur. With its high sensitivity, the STOC allows for very short exposure times, even under moderate lighting conditions. So it is appropriate for high-motion applications, such as outdoor robotics, motion capture, etc. Figure 1-2 shows an example of motion capture using the device. Notice the stop-action motion of the model plane.

Although there are a small number of global-shutter CMOS imagers, most of them are *sequential*, that is, the pixels are exposed, then read out. The pixels cannot be exposed again until readout finishes. With sequential readout, either the framerate or the maximum exposure is limited. The STOC has *simultaneous* exposure and readout, that is, while the pixels are being exposed, the previous image is being read out.

Figure 1-2 Sequence taken by the MT9V022. Exposure 0.7 ms, 30 Hz, 640x480 video stream. Sequence shows about every 4th frame.

2 Quick Start

The STOC/-C normally comes assembled with the lenses mounted. If you need to change the lenses, or if you are supplying your own, please see Section 0.

To set up and test the STOC/-C, you will need the following:

1. Host computer with an IEEE 1394 PCI (desktop) or PCMCIA (laptop) card, OHCI compliant; or a built-in IEEE 1394 port.
2. IEEE 1394 6-pin to 6-pin cable.
3. Small Vision System installed on the host computer.

Install the IEEE 1394 host card, if necessary, according to the directions in Section 4.1. Install the Small Vision System software (see Section 4.2).

Plug one end of the IEEE 1394 6-pin video cable into the 1394 jack on the back of the STOC/-C, and the other into an IEEE 1394 port on the host PC.

Note: The STOC draws power from the IEEE 1394 bus. PCI cards, or built-in ports for desktop machines, normally supply this power. For PCMCIA cards (PC Cards), and laptops with a built-in port, no power is available. In this case, external power must be supplied – see Section 5.3.

The PC operating system will normally recognize the STOC, and install the correct system drivers. Please see the Videre support web pages (www.videredesign.com/support.htm) for specific information about installation for your OS. At this point, you should check to see that the STOC has been recognized by the system.

It takes the STOC device about 20 seconds to configure itself, as it sets up internal calibration tables based on lens parameters. During this time, the LED on the device will blink slowly. When it stops blinking, it should stay lit, indicating the device is recognized by the PC. If it is not lit, then there is a problem with the IEEE 1394 drivers on the PC.

Start the SVS main program, `smallv(.exe)`, on the host computer. You should see a screen as in Figure 2-1. The message window should indicate that the "DCS Digital Stereo Interface" is present. If not, go back to software installation (Section 4.2), and follow the instructions for configuring the correct capture library.

Pull down the Input chooser, and select the `Video` option. If everything has been set up correctly, the SVS interface will recognize and configure the stereo head, and a success message will appear in the info text window. The "Proc Capable" button will light up to indicate the presence of the STOC processor, and the stereo parameter controls will be grayed out, since the STOC has fixed parameters. If not, the Input chooser will go back to `None`, and an error message will appear in the info window. Please see Section 4 for troubleshooting.

To view stereo video, press the `Continuous` button. By default, the STOC device is put into its "Stereo Processing" mode, in which it sends the

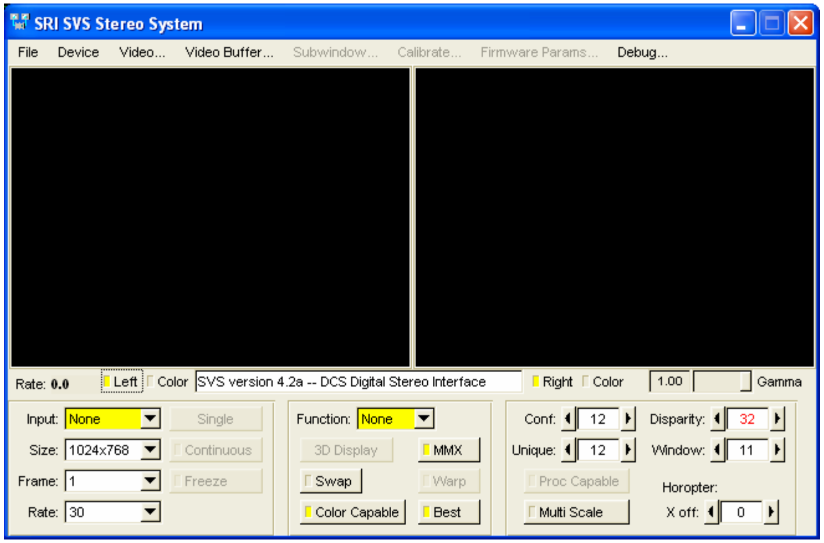


Figure 2-1 SVS main program window.

left image plus the disparity (range) image. In the left window there will be the left image from the camera; in the right image, the disparity image produced by stereo processing. If the message "Image timed out" appears, then there is a problem with the IEEE 1394 drivers; please see Section 4. If the images are too light or too dark, you can change the exposure and gain settings (Section 7.4). Images can be saved using the File menu.

The STOC device is a self-contained ranging device. It produces range information directly on the device, without any computation on the PC. The smallv program displays this information, as well as the original, rectified left image.

You can view a 3D version of the disparity image by converting it into a 3D point cloud. Choose the "3D Display" button, and an OpenGL window will appear, with the range information converted into a point cloud. You can navigate the viewpoint of the window by moving the mouse while holding down the left button.

The STOC has flexible output modes. The default mode is to output the left rectified image and the disparity range information. There are four modes:

1. Left rectified image + disparity (default)
2. Original raw images
3. Rectified images
4. Test image

A more complete description of the video capture options is in Section 7. The SVS interface API and sample programs are described in the SVS User's Manual. It is helpful to review Section 7 in conjunction with the SVS documentation. The SVS Calibration Addendum should be consulted if the calibration is redone – see Section 8.

3 Hardware Overview

Figure 3-1 shows the hardware configuration of the STOC/-C.

The imager module has a milled aluminum alloy frame that rigidly holds two VGA imagers, separated by a fixed distance of 9 cm. Lens mounts are an integral part of the frame, and miniature 12 mm diameter lenses are screwed into these holders. There is an IR cutoff filter, with a knee at approximately 680 nm, permanently mounted inside the lens holder. See Section 6 for appropriate lens characteristics.

The interface module is mounted on the back of the stereo head. One IEEE 1394 port is placed at the back of the module; it is inset so that the IEEE 1394 plug does not stick out from the device.

A status LED indicates video imager activity. When the device is powered and connected to an IEEE 1394 card on the host computer, it will flash slowly during the initialization of the STOC board, for about 40 seconds. At the end of this time, it will stay on if the device has been recognized by the host PC. The LED will begin flashing again as soon as images are being acquired by the host computer, at ½ the frame rate. Changing the video modes (frame size, decimation) will cause the frame rate to change, and this will be reflected in the LED flash rate.

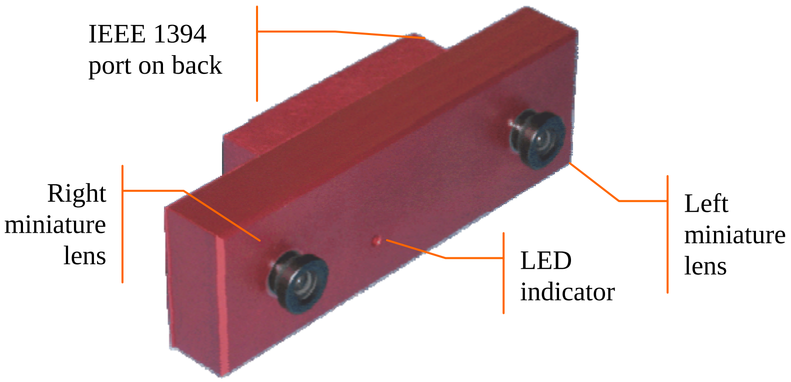


Figure 3-1. Physical layout of the STOC/-C stereo head.

There are no user-settable switches on the STOC/-C.

3.1 Hardware Schematic

Figure 3-2 shows the design of the internal hardware of the STOC/-C. In the stereo imager module, two CMOS imagers, each of size 640x480 pixels, digitize incoming light into a digital stream. The imagers operate in progressive mode only, that is, each line is output in succession from the full frame.

The maximum video rate is 12 megapixels per second from each imager, which produces 640x480 at 30 Hz. The imagers are synchronized to a common clock, so that the corresponding pixels from each imager are output at precisely the same time.

The two digital streams are fed into the STOC board. There, they are first rectified to eliminate lens distortion and mechanical misalignment. Then, the rectified images are processed to extract disparity (range) information at each pixel. The disparity image and the left rectified image are interlaced, pixel by pixel, and sent to the interface board.

On the interface board, the interlaced video stream is transferred to the IEEE 1394 interface module, which communicates to the host PC over an IEEE 1394 digital cable. The module also accepts commands from the host PC over the cable, and uses these commands to control imaging modes such as exposure.

The IEEE 1394 interface module can communicate at the maximum IEEE 1394 data rate, 400 MBps. Of this, the maximum data rate for video transfer is 32 MB/s.

3.2 Frame Formats and Rates

The IEEE 1394 interface electronics on the STOC supports a maximum rate of 32 megapixels per second. At this rate, there is no need for large buffer memories to hold video data on the stereo device. The STOC/-C conforms

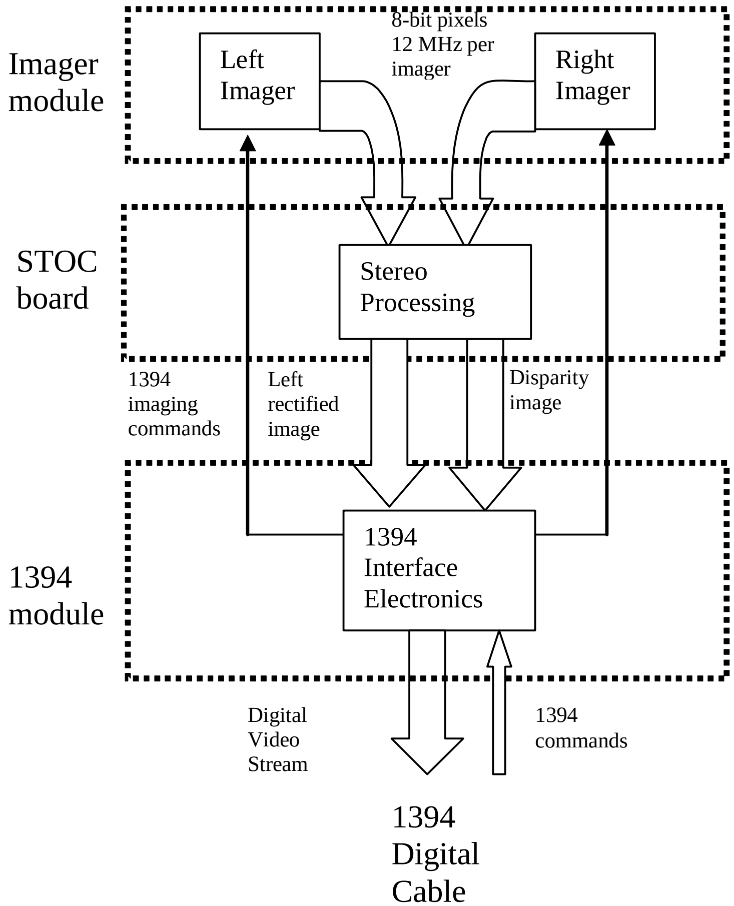


Figure 3-2 Schematic of the STOC/-C electronics. The diagram shows a stereo processing mode. In other modes, stereo processing can be bypassed.

to the IIDC version 1.30 camera specification. Frame rates and frame sizes are set by this standard. The STOC/-C implements the formats shown in **Error! Reference source not found.**.

Format	**Frame size**	**Frame rate (default)**	**Frame rate, 50 Hz option**
Format 0, Mode 3 YUV 16 bits	640x480	7.5, 15, 30 Hz	6.25, 12.5 25 Hz

Table 1 Frame formats and sizes for the STOC/-C.

The Digital Camera Specification was set up with monocular cameras in mind. To conform to this specification, the STH-MDS/-C uses the YUV data type, sending one 8-bit video stream on Y, and another on UV. On the host computer, the SVS interface software takes the YUV stream and parses it into the left and right images, making them available as separate images in computer memory. It also performs color processing, for the STOC-C, converting the Bayer pattern into full-color RGB images.

Because of the limitation of two 8-bit video streams, the STOC device has various *submodes* in which it sends different information on the streams. The choice of video stream types are:

1. Original image (8-bit monochrome or Bayer color pattern)
2. Rectified image (8-bit monochrome only)
3. Disparity image (8-bit disparity image)
4. Test Pattern

Different combinations of these images give rise to the different submodes shown in Table 2. The default mode, shown in gray, is `PROC_MODE_RECTIFIED`. The left and right (monochrome) rectified images are sent back to the PC.

There are two modes in which disparity is computed on the STOC and sent back to the PC. PROC_MODE_DISPARITY sends the disparity and the left rectified (monochrome) image. It is not possible to send a rectified

Format	Submode		
	Y	UV	NAME
Format 0, Mode 3 YUV 16 bits	LO	RO	PROC_MODE_OFF, PROC_MODE_NONE
	LR	RR	PROC_MODE_RECTIFIED
	LR	D	PROC_MODE_DISPARITY
	LO	D	PROC_MODE_DISPARITY_RAW
	TP	TP	PROC_MODE_TEST

Table 2 Submodes for the STOC YUV format.

color image in 8 bits; hence, to send disparity and the color image, `PROC_MODE_DISPARITY_RAW` sends the original left Bayer image (unrectified). Color processing and rectification then takes place on the PC.

To send just the original images to the PC, use `PROC_MODE_OFF`. In this mode, the STOC/-C functions just like an ordinary STH-DCSG/-C.

In the *smallv* application, various combinations of requested features will put the STOC into one of the modes above. In general, *smallv* will try to keep as much processing on the STOC as possible. For example, requesting *Stereo* and *Warp*, without color, will put the STOC into `PROC_MODE_DISPARITY`.

If the *Proc Capable* button is turned off, then the STOC will revert to `PROC_MODE_OFF`, and all processing will take place on the PC.

Under program control, the processing mode can be changed using the `svsVideoImages` object controlling the stereo device. The following member function will set the mode.

```
bool SetProcMode(proc_mode_type mode);
enum proc_mode_type
  {
    PROC_MODE_OFF = 0,
    PROC_MODE_NONE,
    PROC_MODE_TEST,
    PROC_MODE_RECTIFIED,
    PROC_MODE_DISPARITY,
    PROC_MODE_DISPARITY_RAW
  };
```

3.3 Disparity images

The STOC processing board produces a *disparity image*, which encodes the range to objects in the scene. The disparity image has high value (brighter) when an object is closer, and lower value when it is further away. In addition, there are filters that eliminate bad stereo matches – these will appear as dark areas in the image. Figure 3-3 An image from the STOC device, and the corresponding disparity image. shows a typical disparity image from the device.

The disparity image is 10 bits in depth. The search area for stereo matches between left and right images is 64 pixels (6 bits). In addition, the match is interpolated to 1/16 of a pixel, giving and additional 4 bits. The relationship between disparity and 3D XYZ coordinates depends on the lenses and imager characteristics – see the SVS Users' Manual and the Calibration Addendum for more technical information. There are functions in SVS to translate the disparity image into XYZ points.

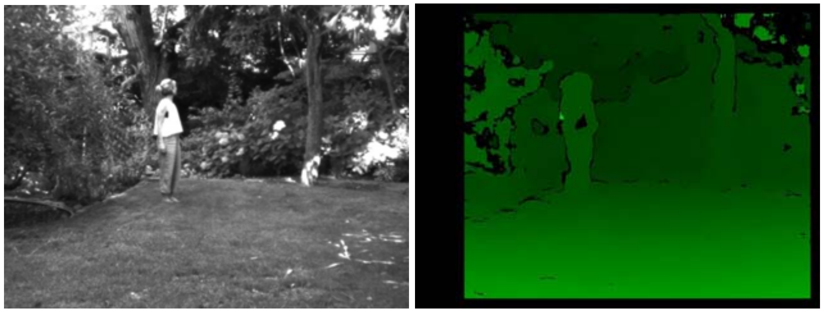


Figure 3-3 An image from the STOC device, and the corresponding disparity image.

In sending video information over the IEEE 1394 bus, the STOC device uses 16 bits/pixel: 8 bits/pixel for the left image, and 8 bits/pixel for the disparity image (default mode). Thus, the disparity image must be compressed. For the first implementation of the STOC, the lower two bits are truncated. Future implementations will use companding (lower values are preserved, higher values are compressed) and 24 bit/pixel IEEE 1394 modes.

3.4 50 Hz Operation

Indoor lighting, especially from fluorescent fixtures, can oscillate at the frequency of the electrical supply. If the image frame rate does not divide evenly into this frequency, there can be moving horizontal bands of alternating light and dark moving in the output.

For countries with 60 Hz power such as the United State, the frame rates in the third column of **Error! Reference source not found.** are ideal. In many other countries, the electrical line frequency is 50 Hz. For these countries, there is a mode to change the frame rates of the STOC to sub-multiples of 50 Hz. These frame rates are shown in the last column of **Error! Reference source not found.**.

The frame rate mode of the STOC device can be changed by using the Firmware Parameter dialog – see Section 7.7.

3.5 Multiple Devices

Multiple STOC devices can be attached to the same IEEE 1394 bus. When streaming video at the same frame rate, they are synchronized, so that they capture images at the same time.

Frame size	**Bus MB per frame - stereo**	**30 / 25 Hz**	**15 / 12.5 Hz**	**7.5 / 6.25 Hz**	**3.75 / 3.125 Hz**
640x480	0.683 MB	20.5 MB	10.2 MB	5.12 MB	N/A
320x240	0.171	5.12 MB	2.56 MB	1.28 MB	N/A

Table 3 Bus bandwidth requirements at different frame rates.

Each IEEE 1394 PC Card or PCI Card defines a separate IEEE 1394 bus. The two or three ports on the card all belong to the same bus, as does any IEEE 1394 hub connected to these ports. Separate PC Cards and PCI Cards cannot be connected to each other.

The number of devices that can simultaneously send video is determined by the maximum bandwidth of the bus for isochronous transfers: 32 MB/s. This rate cannot be exceeded by the combined video streams on the bus.

Table 3 shows the bandwidth requirements for the STOC in various modes and for various frame rates. Using this table, it is possible to determine the maximum number devices that can stream video simultaneously. For example, at 15 Hz and 640x480 resolution, a maximum of 3 STOC devices can send video information at the same time.

The bus bandwidth consumed by a device is more than would be expected from just counting the number of bytes in each frame, because there are blank cycles on the bus, when no data is being transmitted, even though the bandwidth is reserved. Thus, it makes no difference whether the rate is 30 Hz or 25 Hz, the bus bandwidth consumed is the same.

4 Installing the 1394 Host Card and Capture Software

The STOC/-C connects to a host computer via a digital 1394 interface. The host PC must have a 1394 port, and software to interface to the video stream from the camera. This interface software presents the video stream from the 1394 hardware as a set of stereo frames to the user program (see Figure 4-1). The STOC/-C comes with interface software for either MS Windows 98SE/ME/2000/XP or Linux.

4.1 1394 Hardware and Drivers

Before installing the software interface, the PC must be equipped with a 1394 port. If there is one already present, a built-in port, then you can skip this section. Otherwise you have to install a PCI or PCMCIA card. The card must be OHCI compliant, which all current cards are.

4.1.1 MS Windows Hardware Installation

For the most up-to-date information about installation, please see the Videre Design website (www.videredesign.com/support.htm).

MS Windows 98SE, ME, 2000, or XP is required.

For a PCI card, insert the card into a free PCI slot with the computer power off, and start the computer. With a PCMCIA card, insert it into the PCMCIA slot. In either case, the New Hardware wizard will walk you through installation steps for the low-level drivers. You may need your MS Windows OS CD to install some files.

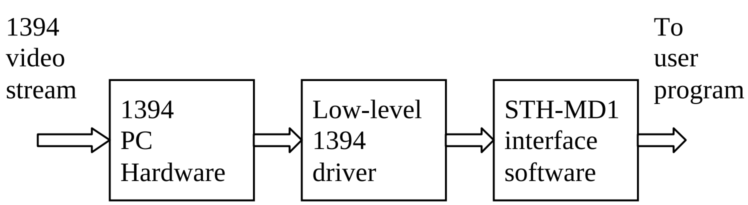


Figure 4-1 Host PC low-level software structure.

The STOC must be powered from the IEEE 1394 bus. Desktop PCs supply power to the bus; laptops do not. See Section 5 for information about cabling and power for the IEEE 1394 bus.

4.1.2 Linux Hardware and Driver Installation

Linux kernels 2.4 or 2.6 kernels are required for operation. Please see the Videre Design website (www.videredesign.com/support.htm) for current information. GCC 3.x is recommended as the compiler; there is a separate SVS distribution for GCC 2.95.x, but it is not as reliable.

4.2 STOC Software

The STOC/-C comes with the SVS stereo software, and several sample applications, including the GUI application described in this manual.

For the most up-to-date information about installation, please see the Videre Design website (www.videredesign.com/support.htm).

To install the software under MS Windows, execute the file `svsXXX.exe`. If you have installed a previous version of SVS, the installation wizard will ask you if you want to un-install the old version. It is best to uninstall the old version, then start the installation file again and install the new one.

The installation process will add the relevant interface and application software.

To install the software under Linux, untar the file `svsXXX.tgz` in a new directory, which will become the top-level directory of the software. You should also set the environment variable SVSDIR to this directory, and add `bin/` to your LD_LIBRARY_PATH variable.

`libsvscap.so` and `svsgrab.lib/dll` are the capture libraries for Linux and MS Windows, respectively. By default, these libraries are set up during installation to the correct ones for the STOC. Should there be any problem, you can re-copy STOC libraries into the library files.

In MSW Windows, execute the file `bin\setup_dcs.bat`. This will copy `svsdcs.dll/lib` as the interface libraries.

Under Linux, copy the following file in the `bin/` directory:

```
dcscap.so -> libsvscap.so  (Linux)
```

You can check that the correct interface library is installed, by looking at the information text when the capture application is started. It should say "DCS digital stereo interface". If not, the wrong interface library is installed in `svsgrab.dll` or `libsvscap.so`.

The directory structure for the software is:

```
bin/
   smallv(.exe)
   smallvcal(.exe)
   smallvmat(.exe)

   svsgrab.dll/lib
   libsvscap.so
   interface libraries
   stereo calculation libraries
src/
   flwin.cpp
   image_io.cpp
   svsclass.h
   svs.h
   flwin.h
samples/
   smallv.cpp
   fldispx.cpp
   *.dsw, *.dsp, makefile
```

There are several applications – see the SVS User's Manual for more information. The source code for all applications is included in the distribution. The stereo calculation libraries are also included, so that user applications can link to them. The calibration libraries are *not* included; the only way to run the SVS calibration procedures is through the `smallvcal(.exe)` application.

`smallv(.exe)` is a GUI-based application that allows the user to exercise the capture and stereo functions of the STOC/-C. It is described in earlier sections of this document.

`smallvmat(.exe)` is similar to `smallv`, with the addition of a MatLab interface for sending images and stereo information to MatLab. You must have installed the R13 release of MatLab to run this program. There is also a version of SVS that can be invoked directly from MatLab – again, see the SVS User's Manual.

`smallvcal(.exe)` is the same as `smallv`, with the addition of a calibration package for calibrating a stereo rig. Use this application to perform calibration on your stereo system.

`stcap(.exe)` is a simple application that connects to the stereo head and displays images. It can serve as a template for user programs that integrate stereo capture from the STOC/-C.

`stdisp(.exe)` is a simple application that connects to the stereo head, grabs images and performs stereo analysis, and displays the results. It can serve as a template for user programs that integrate stereo capture and computation from the STOC/-C.

5 IEEE 1394 Interface

Digital image information is transferred from the STOC/-C to the host PC via a 1394 cable. The cable sends a video stream from the imagers to the PC, and sends commands from the PC to the stereo head to control exposure, subsampling, etc. The cable also supplies power to the stereo head.

5.1 IEEE 1394 Cable

The STOC/-C must be connected to the host PC via a 6-pin male-male IEEE 1394 cable. The maximum length for such a cable is 4.5 m (about 15 feet). The cable supplies both signals and power to the stereo head. The port on the STOC is recessed, so that the IEEE 1394 cable plug will not stick out from the camera.

The distance between the stereo head and the PC can be extended by using a 1394 repeater.

Several 1394-enabled devices can be connected together, as long as the connection topology doesn't have any loops. The STOC/-C can be connected at any point in such a topology. At a maximum, it will need about 60% of the bandwidth of a 400 MBps connection.

5.2 IEEE 1394 Host Interface

The host computer must have an available 1394 port. Some portables and desktops come with built-in ports. If these are 6-pin ports, they can be connected directly to the STOC/-C. Sony laptops also support an alternative 4-pin 1394 cabling, which has the signal pins but no power. There are adapters that convert from 4-pin to 6-pin styles; these adapters use an external power supply transformer.

If the host PC doesn't have a built-in 1394 port, one can be added by installing a 1394 PCI card or PCMCIA card for laptops. 1394 PCI cards have 6-pin ports, and supply power. PCMCIA cards do not have the capability of supplying power, and come with an adapter for supplying power to the 1394 cable through a wall transformer.

Any 1394 card is suitable, as long as it conforms to OHCI (open host controller interface) specifications. All current cards do, but some older cards may not.

5.3 Supplying Power

Power to the STOC is supplied through the IEEE 1394 cable. The IEEE 1394 system must supply this power, about 2.4 Watt.

There are two typical PC systems: desktops and laptops.

- Desktop PCs have either a built-in IEEE 1394 port, or a PCI card with IEEE 1394 ports. In both cases, the desktop should supplysufficient power to run the STOC.
- Laptop PCs have either a built-in IEEE 1394 port, or a plug-in PC Card (sometimes called a PCMCIA card) with several IEEE 1394 ports. In both cases, the laptop does *not* supply power to the IEEE 1394 bus, and a source of external power must be used – see below.

External power to the IEEE 1394 bus must have the following characteristics:

7 to 16 VDC, > 3 W

The IEEE 1394 spec allows up to 40 VDC on the bus, but in practice many devices such as PC Cards will fail if a voltage higher than 16 VDC or so is used. We recommend using a 12 VDC source.

Power can be supplied to the bus through an IEEE 1394 hub or PC Card with an external port. Most hubs have such a port; most PC Cards do not. The PC Card supplied by Videre has a power port.

The format of the power plug can vary with the hub or PC Card, so please check the specifications for the device. Generally, the positive terminal of the plug is on the inside, and the negative is the outside cylinder.

Figure 5-1 shows the two configurations for supplying power. A wall transformer converts line voltage to 12 VDC, and is plugged into a hub or the PC Card.

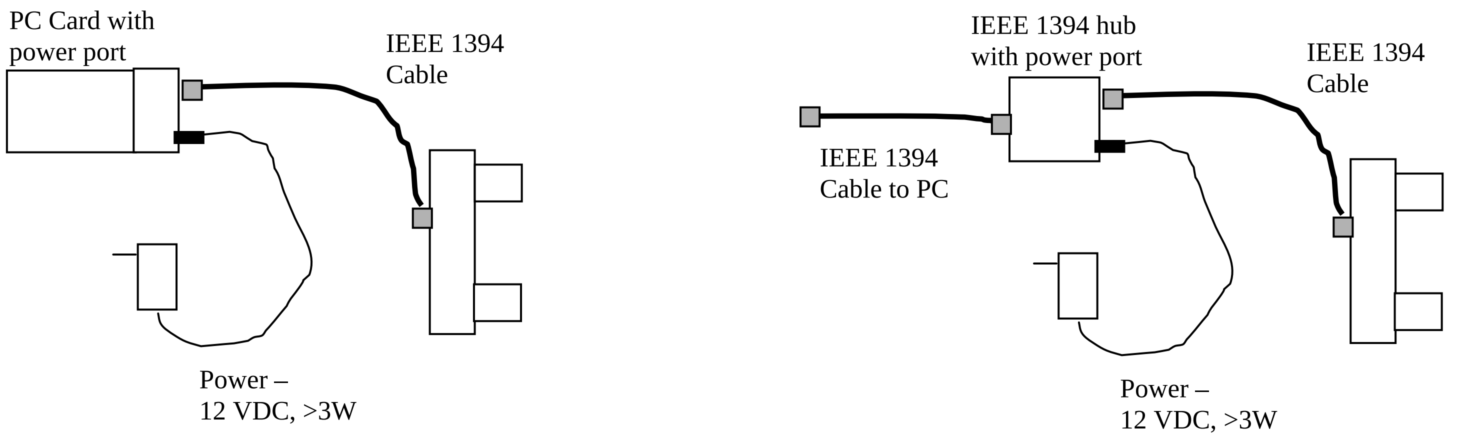


Figure 5-1 External power supply connections. On the left is power supplied to a PC Card with a power port. On the right, power is supplied through a hub with a power port. Power should be 7 to 16 VDC, at > 1.5 W. Check the PC Card or hub for the type of power connector.

6 Lenses

The STOC/-C uses either 12mm diameter miniature lenses, or CS-mount locking lenses. Miniature lenses are screwed into integral lens-holders milled into the aluminum chassis. The lenses are focused at the factory, and firmly glued into place. There are no adjustments to be performed on the lenses. It is possible to change both types of lenses, although changing the miniature lenses is not recommended; see Section 6.7 and 6.8 below.

Lenses are characterized optically by imager size, F number, and focal length. Following subsections discuss the choice of these values.

6.1 Cleaning the Imagers

It should not be necessary to clean the imagers, since they are sealed off by an IR filter inside the lens mount.

6.2 Imager Size

The *imager size* is the largest size of imager that can be covered by the lens. The STOC imager is 1/3" size (about 6mm in diameter).

6.3 F Number

The *F number* is a measure of the light-gathering ability of a lens. The lower the F number, the better it is at pulling in light, and the better the STOC will see in low-illumination settings. For indoor work, an F number of 1.8 is acceptable, and 1.4 is even better. For outdoors, higher F numbers are fine. Miniature lenses do not have any iris control; instead, they rely on electronic exposure and gain control to automatically compensate for different light conditions.

6.4 Focal Length

The *focal length* is the distance from the lens virtual viewpoint to the imager. It defines how large an angle the imager views through the lens.

The focal length is a primary determinant of the performance of a stereo system. It affects two important aspects of the stereo system: how wide a field of view the system can see, and how good the range resolution of the stereo is. Unfortunately there's a tradeoff here. A wide-angle lens (short focal length) gives a great field of view, but causes a drop in range resolution. A telephoto lens (long focal length) can only see a small field of view, but gives better range resolution. So the choice of lens focal length usually involves a compromise. In typical situations, one usually chooses the focal length based on the narrowest field of view acceptable for an application, and then takes whatever range resolution comes with it.

6.5 Field of View

The field of view is completely determined by the focal length. The formulas for the FOV in horizontal and vertical directions are:

$$HFOV = 2\arctan(1.92/f)$$

$$VFOV = 2\arctan(1.44/f)$$

where f is in millimeters. For example, a 2.8 mm lens yields a horizontal FOV of 87 degrees.

Table 4 shows the FOV for some standard focal lengths.

Lens focal length	**Horizontal FOV**	**Vertical FOV**
2.1 mm	85 deg	69 deg
3.6	56	44
5.7	37	27
8.0	27	20

Table 4 Horizontal and vertical field of view for different lens focal lengths.

6.6 Range Resolution

Range resolution is the minimum distance the stereo system can distinguish. Since stereo is a triangulation operation, the range resolution gets worse with increasing distance from the stereo head. The relationship is:

$$\Delta r = \frac{r^2}{bf}\Delta d ,$$

where b is the baseline between the imagers, f is the focal length of the lens, and Δd is the smallest disparity the stereo system can detect. For the STOC/-C, b is 90 mm, and Δd is 0.375 um (pixel size of 6.0 um, divided by the interpolation factor of 16).

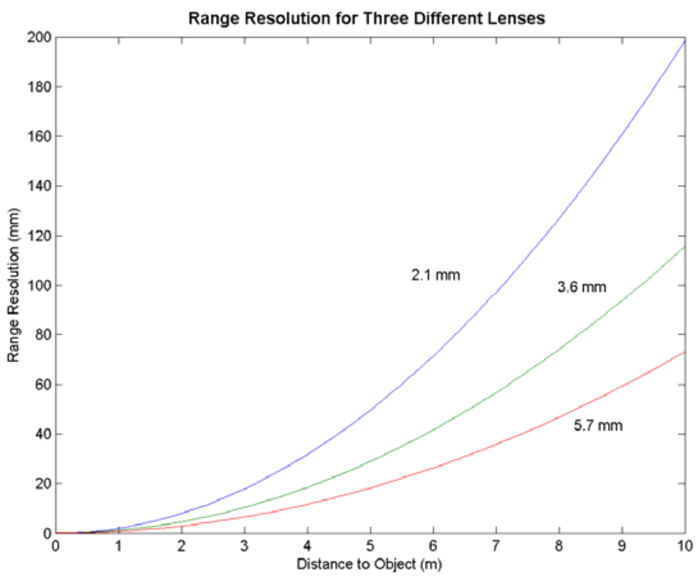


Figure 6-1 Range resolution in mm as a function of distance, for several different lens focal lengths.

Table 4 plots this relationship for several focal lengths. At any distance, the range resolution is inversely proportional to the focal length.

6.7 Changing Miniature Lenses

The STOC comes with 12 mm diameter miniature lenses glued firmly in place. We do not recommend changing the lenses, but it is possible to do. If the lenses are changed or in any way moved, then the device will lose its calibration, and a calibration must be performed and the results downloaded to the device (see the Calibration Addendum for information about performing the calibration step). Section 8 has information about how to download a calibration file to the STOC.

While the lenses have been glued into their holders, the hold of the glue can be broken, and the lenses removed. Doing so may damage the lenses, and for this reason we do not recommend changing them.

To remove the lenses, use a pliers with a soft tissue around the top of the lens, to prevent scratching from the plier jaws. Grab the lens head firmly with the pliers, and rotate counter-clockwise. The lens should rotate in its socket, but it takes some force to do this.

Once the lens has been removed, use pressurized air to clean out the lens holder. Then install the new lens, which should have a 12 mm diameter barrel, with a screw pitch of 0.5 mm. Install the lens as described below, and check for a good focus.

The screw mates with the lens holder opening. To insert a lens, place its back end on the lens holder opening as straight as possible, and slowly turn it counter-clockwise (looking down at the lens), applying some slight pressure, until you feel a small "click". This indicates that the threads are in a position to engage. Without removing pressure, rotate clockwise until the threads of the lens engage the lens holder. If you encounter a lot of resistance, you may be cross-threading the lens. Forcing it on at this point will damage the lens holder or lens threads.

Once the threads are engaged, continue screwing it on until some portion of the thread on the lens barrel is in the lens holder. Then, plug in the device, and start video streaming (in Original Image mode). Screw the lens down

while watching the video. You should be able to get a good, sharp image. Screwing down too much past the point of good focus can damage the internal IR filter, so be careful here.

Once you have found a good focus, unscrew the lens until its barrel is almost out. Then apply a small amount of Lok-Tite or similar threadlocking compound. These compounds come in several strengths; use a light-strength one if you intend to remove the lens.

Screw the lens in again until you get a sharp image. Then, let the threadlocker set, usually about 10 minutes.

Once both lenses are installed, you will need to re-calibrate the device, and upload the calibration to the STOC. Please see Section 8

6.8 Replacing and Adjusting CS-Mount Locking Lenses

Any adjustment or replacement of CS-mount lenses on the STOC should be followed by re-calibration of the STOC device (Section 8).

CS-mount lenses come with thumbscrew locks for holding the focus and iris settings. They are set at the factory, usually with the iris wide open and the focus set to infinity.

If you need to adjust the focus or iris, then it is a good idea to re-calibrate Adjusting the focus or iris usually results in changing the internal camera parameters, and the calibration will suffer.

It is easy to replace CS-mount lenses. To remove the lens, unscrew the lens counter-clockwise. There will be some initial resistance, and then it should unscrew smoothly.

CS-mount lenses have a 1" diameter, 28 threads-per-inch screw on their back end. The screw mates with the lens holder opening. To insert a lens, place its back end on the lens holder opening as straight as possible, and gently turn it clockwise (looking down at the lens) until it engages the threads of the lens holder. If you encounter a lot of resistance, you may be cross-threading the lens. Forcing it on will damage the lens holder or lens threads.

Once the threads are engaged, continue screwing it on until it seats firmly. You can snug it down, but do not tighten it excessively, since this can damage the lens and the lens holder threads.

Normal care should be used in taking care of the lenses, as with lenses for any good-quality camera.

7 User Controls

The CMOS imagers are fully controllable via the 1394 interface. User programs may input color images (STOC-C only), set video digitization parameters (exposure, gain, red and blue balance), and subsampling modes. All of these parameters can be set with the SRI Small Vision System. They are also accessible to user programs through the capture API (Section 8).

User controls for frame size and sampling modes are on the main capture window dialog. Video digitization controls are accessed through a dialog invoked with the *Video…* menu item. Figure 7-1 shows the dialog.

7.1 Submode

The submode specifies what video streams are output by the STOC. There is an API call in SVS to set the submode directly – see the SVS Users' Manual. In smallv, the submode is set indirectly, by the Function and Warp inputs. The default submode, left rectified image and disparity image, is set by using Function->Stereo and turning Warp on. By default, this is done when the STOC is first opened. Setting Function->None turns off stereo processing, and outputs the right rectified image in place of the disparity image. Turning off Warp will output both original images. Table 5 summarizes these settings. Note that it is not possible to invoke the Test Submode from smallv.

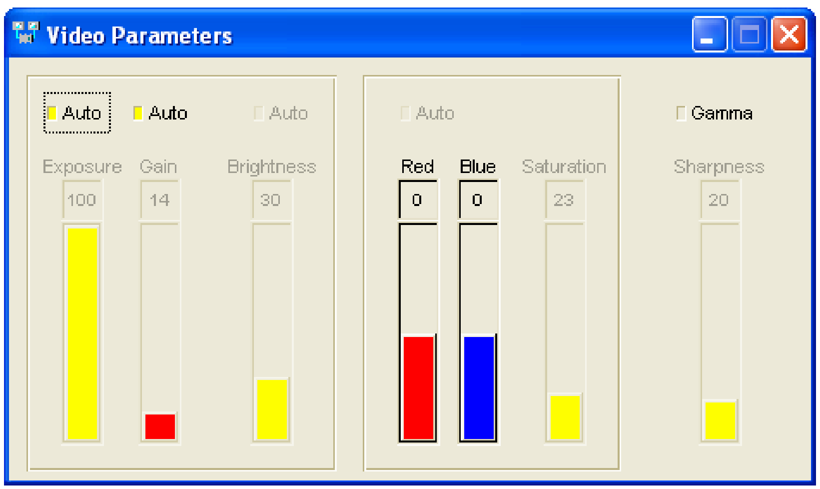


Figure 7-1 Video Parameters dialog.

Function	Warp	Submode
None	Off	LO, RO
None	On	LR, RR
Stereo	On	LR, DP
Stereo	Off	Not available

Table 5 Submodes invoked by settings in smallv.

7.2 Color

Color information from the stereo digital head (STOC-C only) is input as raw colorized pixels, and converted by the interface library into an RGB color channel. The primary color channel corresponds to the left image, which is the reference image for stereo. The right image color channel is not available. The color images will be de-warped to take into account lens distortion, and are aligned with the disparity image.

Color information from the camera is input only if the `Color` button is pressed on the main window (Figure 2-1).

Because the typical color camera uses a colorizing filter on top of its pixels, the color information is sampled at a lower resolution than a similar non-colorized camera samples monochrome information. In general, a color camera has about ¼ the spatial resolution of a similar monochrome camera.

The relative amounts of the three colors, red/green/blue, affects the appearance of the color image. Many color CCD imagers have attached processors that automatically balance the offsets among these colors, to

produce an image that is overall neutral (called *white balance*). The STOC-C provides manual color balance by allowing variable gain on the red and blue pixels, relative to the green pixels. Manual balance is useful in many machine vision applications, because automatic white balance continuously changes the relative amount of color in the image.

The manual gain on red and blue pixels is adjusted using the *Red* and *Blue* controls on the *Video Parameters* dialog. For a particular lighting source, try adjusting the gains until a white area in the scene looks white, without any color bias.

7.3 Gamma Correction

To display properly for human viewing, most video images are formatted to have a nonlinear relationship between the intensity of light at a pixel and the value of the video signal. The nonlinear function compensates for loss of definition in low light areas. Typically the function is x^{γ}, where γ is 0.45, and the signal is called "gamma corrected."

The STOC has on-chip gamma correction that can be turned on or off. When on, it compresses the 10-bit output of each pixel into 8 bits. The compression occurs mostly in the higher light levels. With on-chip gamma correction, the STOC can handle larger dynamic ranges of light, such as occur outdoors with bright sunlight and deep shadow.

Without on-chip gamma correction, the display looks very dark in low-light areas. You can add gamma correction to the displayed image by choosing an appropriate gamma value in the slider under the right display window (Figure 7-2).

7.4 Video Digitization Parameters

The CMOS imagers have electronic exposure and gain controls to compensate for varying lighting conditions. The exposure can vary from a maximum of a full frame time to a minimum of one line time. Gain is an additional amplification of the video signal, for low-light situations. It is settable from 0 to 12 dB (1x to 4x).

Both imagers are treated in exactly the same manner. It is not possible to set a different exposure or gain on each imager.

Digitization control can operate in either manual or automatic mode. Refer to Figure 7-1 for the controls in the video capture program. Both manual and automatic modes are available for the STOC(-C) devices.

In manual mode, the user program sets the exposure and gain. The exposure and gain are based on a 0 to 100 scale. Here are some tips for setting exposure and gain.

- In general, keep the gain as low as possible, since it introduces additional noise into the system. Use it only if the exposure is set to maximum, or if the exposure must be kept low to minimize

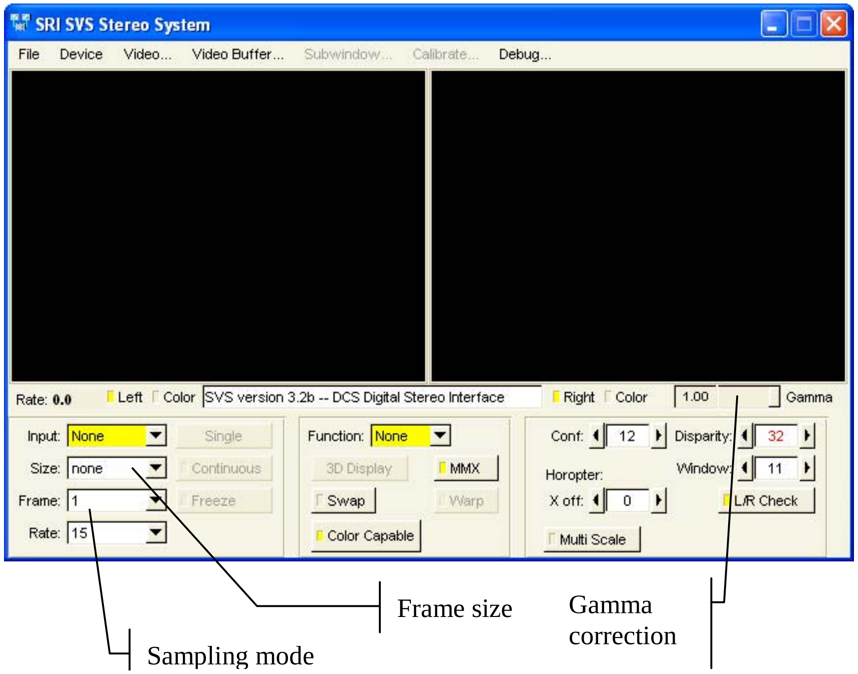


Figure 7-2 Frame size and sampling controls in the main capture window.

motion blur. Indoors, the gain is usually set higher because of the lower light levels.

- Adjust the manual iris of the lens to as small an opening as possible for your application, without having to use gain. This will increase the depth of field and give better optical performance. Indoors, the iris usually is fully open. Outdoors, in bright conditions, the iris can be partially closed.

There are automatic modes for both exposure and gain. In auto mode, gain and exposure are controlled by the imager, which samples the incoming image and sends changes the exposure and gain parameters. The auto algorithm will try to reduce gain as much as possible, while still maintaining overall light levels in the image.

Auto mode for gain and exposure can be set separately. For the STOC, if there is relatively slow motion, it is recommended to use a manual mode for gain, and auto mode for exposure. Indoors, set the gain to a higher value; outdoors, set it to a low value. With exposure in auto mode, the light on the image will be adjusted by changing the exposure.

For high-speed motion, it is better to set the exposure to a fixed, low value, and then use auto-gain to keep reasonable light levels on the imager.

7.5 Subsampling

The STOC device does not perform subsampling operations. All images are transmitted at a resolution of 640x480.

7.6 Frame Rates

Frame rates from the STOC/-C depend on the frame size. Table 6 shows the frame rates available for each of the frame sizes. Note that a 50 Hz option is available – see Section 3.3

7.7 Firmware Parameters

There is one firmware parameter that affects the overall behavior of the STOC.

- 50 Hz operation

This parameter can be changed by using the Firmware Parameter dialog, which is only available from the `smallvcal` menubar. Choosing this menu brings up the dialog, which is shown in Figure 7-3.

The dialog lists many of the internal parameters of the device, which are fixed in the firmware. The one changeable parameter is for 50 Hz or 60 Hz operation (Section 3.3).

The Firmware Parameter dialog is only available after the STOC has been opened by pulling down the `Video` item of the `Input` chooser. To use 50 Hz operation, check the box, and then press the `Save` button. This choice is downloaded and stored in the device, and will cause 50 Hz operation every time the STOC is accessed. To change back to 60 Hz, uncheck the box and again save it to the device.

It is also possible to clear any calibration parameters that are saved on the STOC firmware. If the calibration parameters are present, the Clear Calibration button will be activated. Pressing this button will clear the parameters. See the SVS Users' Manual for information on saving and loading calibration parameters on the device.

Resolution	**Frame**	**Bin on imager**	**Bin on PC**	**Frames per Second**
640 x 480	Full	no	no	7.5, 15, 30

Table 6 Frame rates for the STOC.

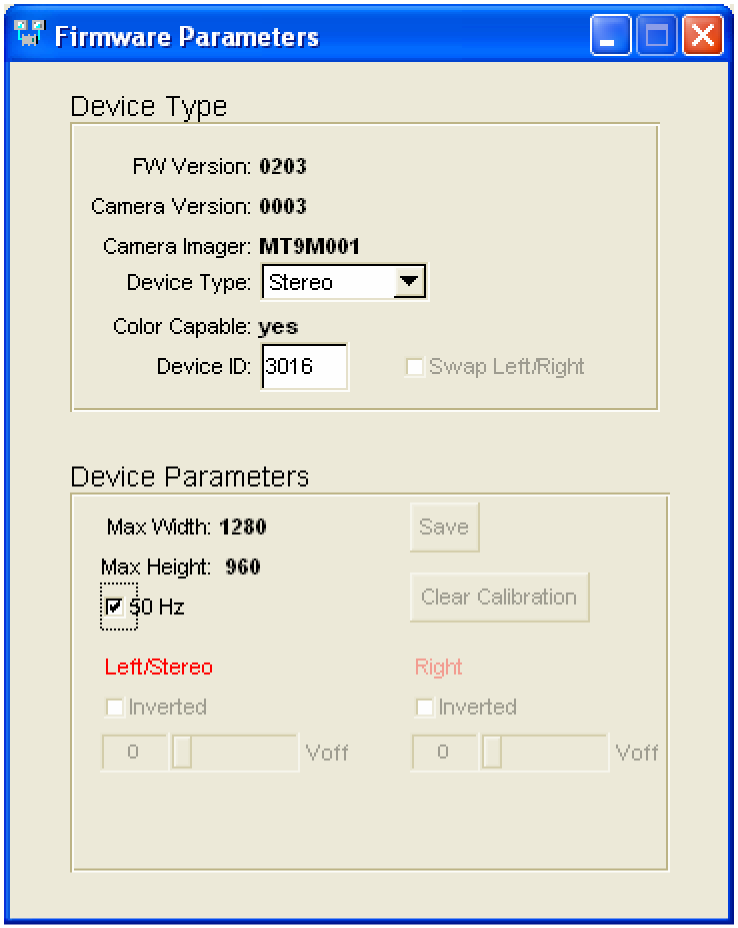


Figure 7-3 Firmware parameters dialog.

8 Redoing Calibration

Whenever the lenses are changed, or the focus or iris is adjusted, it is recommended to perform a re-calibration of the STOC device. This requires the following steps:

1. Do not use any other Firewire devices during re-configuration, including Firewire external disk drives.
2. Erase the current calibration. The current calibration is stored on the device. It can be erased using the `bin/smallvcal` program. Plug in the device, start the program, and open the device (choose `Video` from the `Input` pulldown). Once the device is opened, the Firmware menu item will become available. Click on this item to open the firmware dialog. Click on the `Clear Cal` button.
3. Exit the `smallvcal` program. Now perform a calibration, using the guidelines in the Calibration Addendum. Some things to note:
    a. **Make sure to use un-rectified images as input. The `Warp` button should be off.**
    b. For the target, a square size of 100 mm or larger is recommended for a good calibration.
    c. After calibrating, save the calibration to a file for backup. Then send it to the main program, using the `Send` button.
4. At this point, you should have a valid calibration, and it should be loaded into the main `smallvcal` window, either by using the `Send` button from the calibration dialog, or by loading it from a file using the `File->Load Parameters` menu item. In the Firmware dialog, choose `Upload Cal` to save the calibration to the device.
5. Once the calibration is uploaded to the device, the FPGA can be re-configured. Choose the `Config STOC` button in the Firmware dialog. A file chooser dialog will appear, allowing you to select the FPGA configuration file. The chooser should be at the `bin/` directory; if it is not, navigate to this directory. Then choose one of the following files:
    a. `do_sys.dat` [monochrome system]
    b. `do_sys_color.dat` [color system]

   Configuration will now take place, and will require about 15 minutes. During this time, do not use the Firewire system for other tasks. It is ok to run other programs, as long as they do not access the Firewire bus. If anything interrupts the configuration, you can start over from step 4.

   The Debug window will show the progress of the configuration. First the FPGA program will be downloaded and verified, then the rectification information for the left and right images. At the end, there will be a message indicating successful configuration.
6. Quit the `smallvcal` program, unplug the STOC device, and plug it back in. It should go through its normal startup procedure, with the light blinking for about 20 seconds.
7. Start `smallv` and verify the operation of the device.

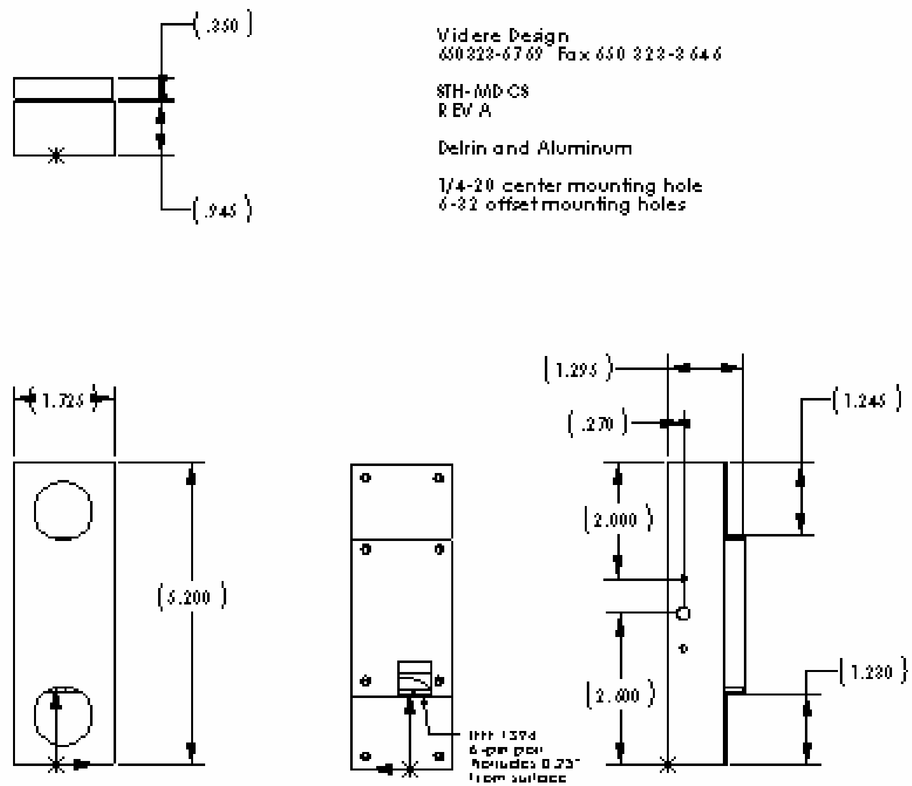
If there are any problems with re-configuration, or if the device does not work properly after re-configuration, please contact Videre Design.

9 Interface Software API

Please see the Small Vision System manual for information about the software API for capturing and saving images.

10 Physical Dimensions and Mounting Diagram

The diagram below shows the physical dimensions for the STOC/-C. The larger hole is threaded for a ¼-20 machine screw (standard tripod mounting screw). The two smaller holes are threaded for 6-32 machine screws.

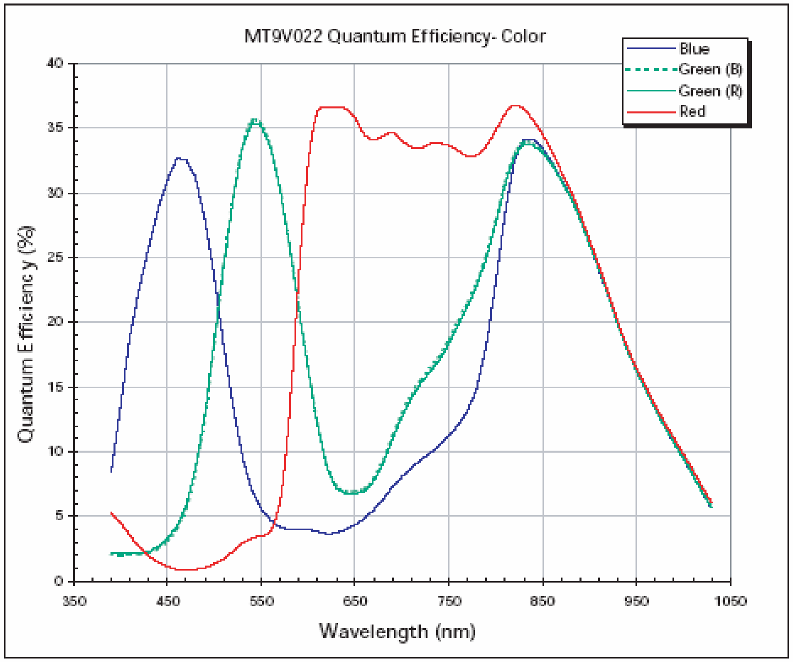


11 Technical Specifications

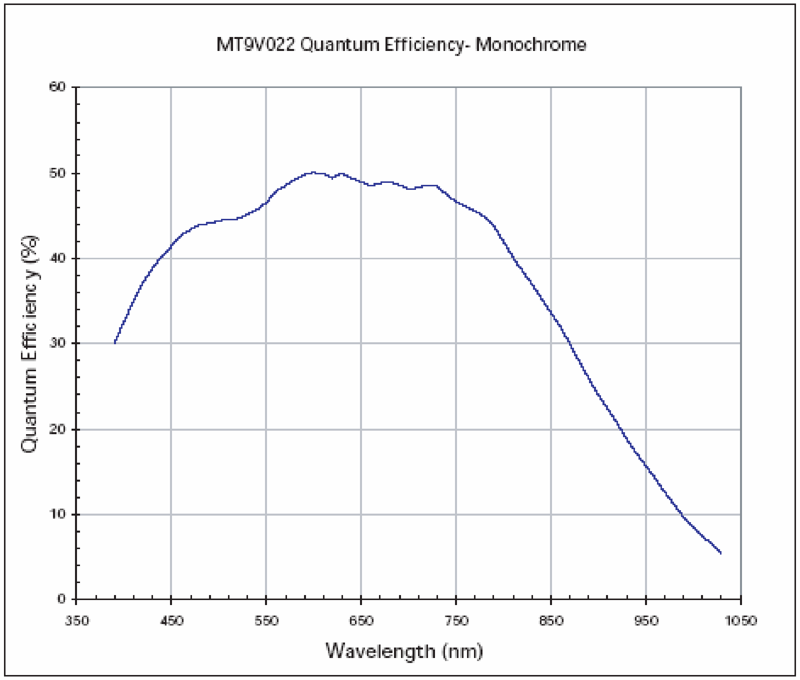
11.1 Specifications

STOC processor	Xilinx Spartan 3 - 1000
Processor performance	35 Gops at 84 MHz
Number of disparities	64 pixels; 1/16 pixel interpolation
Correlation window size	15x15 pixels
Laplacian of Gaussian kernel	9x9 pixels
Post-filtering	Texture and uniqueness check
Imagers	1/3" format CMOS (Micron MT9V022) 640x480 active area Global shutter Progressive scan Color or monochrome
Digital Camera Specification	Version 1.30
Format	640x480 8 bit monochrome or Bayer color pattern 10 bit disparity
Frame Rates	7.5, 15, 30 Hz 6.5, 12.5, 25 Hz Max 30 Hz at 640x480
Exposure	1 line time to full frame
Gain	0 – 12 dB (1x – 4x)
Sensitivity	4.8 V/lux-sec (monochrome)
S/N	> 60 dB, no gain
Power	Imagers and FW interface: 1.45 W STOC board: 0.84 W Total: 2.29 W
Synchronization	Internal: pixel-locked External: 60 us
Lens	3.6 mm miniature lenses standard Other lenses optional (2.1 to 16 mm)
Size	1.725" high x 5.2" long x 1.55" deep (excluding lenses)
Weight	190 g (6.7 oz), without lenses 71 g (2.5 oz) for 4.0 mm lenses
Stereo Baseline	9 cm
SVS software	Linux kernel 2.4, 2.6 MSW 98SE, ME, 2000 and XP
Environmental	0-40^{o} C, < 90% humidity (noncondensing)

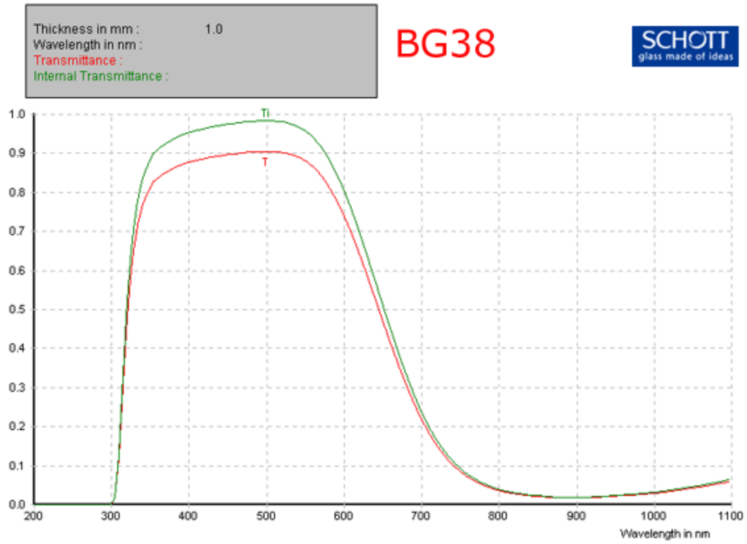
11.2 Imager Response - Color



11.3 Imager Response – Monochrome



11.4 Filter Transmittance



12 Technical Support

For technical support, please contact Videre Design by email or FAX.

Videre Design
865 College Avenue
Menlo Park, CA 94025
Fax: (650)323-3646

Email: support@videredesign.com

Technical information about stereo algorithms and stereo calibration can be found at `www.ai.sri.com/~konolige/svs`.